Science & Global Security, 21:134–163, 2013
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ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929882.2013.798993

Routledge
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The Cost of Recovering Uranium from Seawater by a Braided Polymer Adsorbent System

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This article provides an independent cost estimate for uranium production from seawater through the braid-type adsorbent recovery system proposed by the Japan Atomic Energy Agency (JAEA). Production costs were developed with standard engineering cost estimation techniques using vendor data and plant design and operational data. The analysis includes life cycle discounted cash flows, economies of scale, and propagation of uncertainties. A reference case based on the Japan Atomic Energy Agency assessment, with a fresh adsorbent capacity of 2 kgU/t ads and 6 recycles, yielded a production cost of $1230/kg uranium with a 95 percent confidence interval of [$1030/kg U, $1430/kg U] when component cost uncertainties alone were considered. Sensitivity studies confirmed that adsorbent capacity, number of recycles, and capacity degradation are major cost drivers. If capacity and number of recycles increases to 6 kg U/t ads and 20, respectively, with no degradation and unchanged adsorbent production costs, the uranium production cost drops to $299/kg U.

Supplemental materials are available for this article. Go to the publisher's online edition of *Science & Global Security* to view the free online appendix with additional tables and figures.

INTRODUCTION

The vast uranium resource contained in seawater may play a crucial role in reducing uncertainty as the nuclear power industry develops. If production costs can be reduced, seawater uranium may serve as a "backstop" to conventional uranium resource prices. Backstop resources are those which are available in essentially limitless quantities and displace an exhaustible resource when the

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average production cost of the resource rises to equal that of the backstop.[1] Hence, the uranium production cost is an important viability measure of technologies for recovering uranium from seawater.

The Japan Atomic Energy Agency (JAEA) has led research in the production and performance evaluation of amidoxime adsorbents for uranium extraction from seawater[2]; JAEA produced a cost analysis for this system.[3] Previous work by the authors reviewed and reproduced the JAEA results, identified critical cost drivers, and highlighted points in the production chain where research and development (R&D) is needed to reduce system costs or address uncertainties in performance parameters.[4]

The objectives of this article are to document an independent estimate of the cost of recovering uranium from seawater using the JAEA technology and to establish performance targets for the technology to serve as an effective backstop to uranium prices. To that end, the basic process mass flows will continue to mirror the JAEA design. However, the current work will develop original estimates of all underlying capital and operating costs and key performance and sizing variables within the process areas. An online Appendix to this article provides the process flow diagrams and details of the cost estimation methodology and calculations.

The incorporation of uncertainties is an important element of this work. Discrete point estimates of the uranium production cost can be misleading because they do not reflect the uncertainties in the component costs or the performance of the technology itself. This article develops uncertainties in parallel with cost estimates.

OVERVIEW OF BRAID ADSORBENT SYSTEM

Figure 1 depicts the recovery process studied by JAEA, highlighting three major processes: adsorbent production, mooring, and deployment of the adsorbent, and desorption-purification of the recovered uranium. Figure 2 provides a conceptual view of the braid adsorbent and mooring system. The adsorbent field depicted in the figure is sized for the recovery of 1,200 tonnes of uranium per year. An eight meter spacing between the 60 meter tall braids aims to minimize tangling.

The adsorbent production process includes melt spinning of the base polymer for the adsorbent, polyethylene, into fibers. The fibers are subsequently modified by e-beam irradiation to allow grafting of amidoxime and hydrophilic functional groups to the polyethylene backbone. High surface area fibers increase the effectiveness of the grafting process. The amidoxime groups serve as a selective ligand for complexation of uranium and the hydrophilic functional groups improve fiber contact with seawater. The modified polyethylene fibers are braided around a low-density core structure (such as polypropylene); the open structure of the braid adsorbent maximizes contact area with the

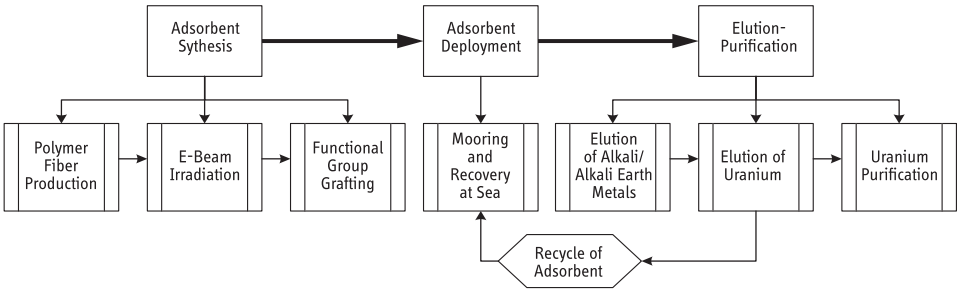

Figure 1: Uranium extraction from seawater—process overview.

seawater while the buoyancy of the braids minimizes support structure required in mooring (see Figure 2).The process diagrams are given in the online Appendix A. The adsorbent performance is characterized by capacity (kg U/tonne adsorbent), which in turn is a function of time immersed and the temperature of the seawater (see online Appendix D for details).

The braided adsorbent material is carried to the deployment site by work boats and subsequently moored to the ocean floor with anchor chains as depicted in Figure 2. At the end of the mooring period, the boats recover the adsorbent material and return it to shore for uranium recovery.[5] Another option, not addressed in this article, would be to recover the uranium at sea, either

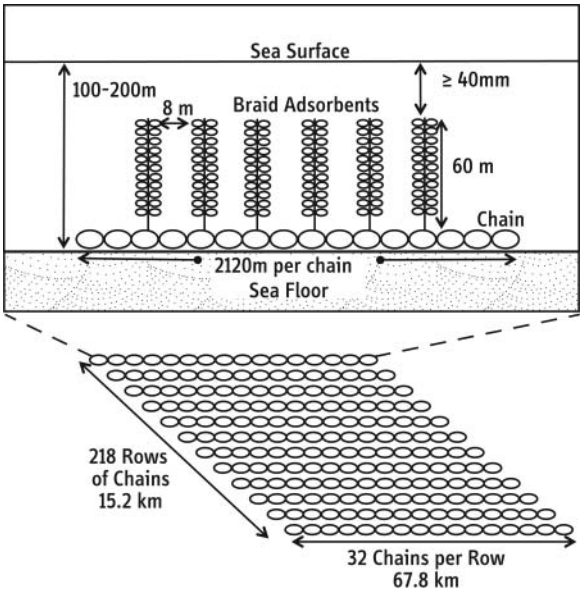

Figure 2: Braid adsorbent and mooring system (Sugo, Takanobu, et al., 2001).

through elution equipment placed on board each work boat or at a centrally located platform or mother ship.

The recovery process consists of consecutive acid elution steps. The first step uses hydrochloric acid to selectively remove alkali and alkali earth metals while the second uses nitric acid to remove uranium. Elements including lead, iron, nickel, cobalt, aluminum, and potassium are adsorbed in amounts comparable to that of uranium.[6] Some of these species occupy the uranium binding sites, so their removal is critical if the adsorbent is to be reused. None of the listed elements can be considered an economically attractive co-product. Measurements of the uptake of potentially viable co-products, for instance rare earths and precious metals, have not yet been published.

The braid adsorbent may be regenerated by an alkali wash after the acid elution steps and returned to sea for repeated use. The uranyl nitrate solution from the second acid elution proceeds to uranium precipitation and purification processes identical to those used in standard uranium mining and recovery processes. The process diagrams are given in the online Appendix (part A).

The next section will offer an overview of the cost estimation techniques used and detailed component cost estimates for each of the three major process areas outlined in Figure 1. Next, an overview of the methods used to estimate the unit uranium production cost for the process is provided, including incorporation of uncertainty in cost and performance inputs. Finally, the results of cost and uncertainty assessment are presented.

INPUT COST ASSESSMENT

This section describes the methods used to obtain independent estimates of all cost inputs. Cost inputs include capital and operating costs (e.g., capital equipment, labor, materials, etc.). To ensure that the costs are treated in a consistent, systematic manner, the data is organized using a code of accounts (COA) system.

The Economic Modeling Working Group (EMWG) of the Generation IV International Forum (GIF) produced detailed cost estimation guidelines for nuclear fuel cycle facilities that will provide the framework for the subsequent analysis; specifically, the guidelines provide a COA that defines cost categories and organizational structure.[7] Discussion of the COA and structure used in the current work can be found in the online Appendix (part B).

OVERVIEW OF ESTIMATION METHODS

A method of cost estimation must be chosen based on the level of information available regarding the process, equipment, and associated costs. The cost estimate in this analysis will conform to the Japanese plant design and process

(Table 1). Therefore, despite the fact that the braid adsorbent process is still in early development, bottom-up assessment is possible where JAEA has provided detailed design information (e.g., specific chemical stream flows, equipment sizing, building or land requirements, etc.). Top-down assessment is used where sufficient detail is not available. Previous work by the authors includes further background on cost estimation techniques used in this analysis.[8]
Cost-estimation was further organized by three process areas:

- adsorbent production,
- mooring and deployment,
- elution and purification.

Each process area has its own COA (accounts 1–9). Within each process area, the following steps were performed:

1) Develop Block Flow Diagram (BFD) or Process Flow Diagram (PFD);
2) Generate equipment and stream lists for each process area;
3) Estimate sizes and cost for major equipment from known throughput information;
4) Use purchased equipment cost to estimate Total Capital Investment Cost (TCIC);
5) Estimate labor requirements based on PFD and equipment list;
6) Develop chemical and utilities cost from stream summaries and price references;
7) Populate COA.

ADSORBENT PRODUCTION

Adsorbent production involves three steps: fiber spinning, irradiation, and grafting. The adsorbent consists of 50,000 tonnes of high density polyethylene (HDPE) grafted with amidoxime functional groups at a 100 percent degree of grafting (DOG), defined as

$$DOG(\%) = \frac{w_G - w_O}{w_O} * 100 \tag{1}$$

where

W_G = Weight of grafted polyethylene (100,000 tonnes)
W_O = Weight of ungrafted polyethylene (50,000 tonnes)

The 100 percent grafting target specified by JAEA provides the sizing basis for the adsorbent production process.

Table 1: Reference case design parameters.

Parameter	JAEA	Current analysis	Unit
Annual Uranium Production	1200	1200	tonnes/year
Seawater Temperature	25	25	°C
Adsorption Capacity	2	2 +/− 0.5	kg U/ t adsorbent[1]
Length of Mooring Campaign	60	60	Days
Adsorbent Recycles	6	6	N/A
Adsorbent Degradation Rate	0%	5 +/− 2.5%	% per recycle*
Discount Rate	0%	7%	annual rate
Interest Rate of Capital	3%	10%	annual rate
Amortization Period: Buildings	30	30	Years
Amortization Period: Equipment	15	15	Years
Interest During Construction	No	Yes	N/A
Disposal Costs	No	Yes	N/A

[1]Expected values of adsorption capacity parameters with corresponding uncertainty. Uncertainty in the parameters are quantified and discussed in text.

Figure A.1 and Figure A.2 in Appendix A depict the PFD for adsorbent production; Table A.1 and Table A.2 define the equipment and streams associated with the PFD. HDPE chips or pellets are fed to single-screw extruder (denoted by A in the in the PFD and equipment table) which uniformly melts the polymer. The polyethylene melt is pumped (B) through a filter (C) and finally to a spinneret (D) for fiber formation. The fibers leaving the spinneret are cooled using filtered air (E), stretched by a godet roll (F), and wound on a take up device (G) in preparation for further processing.

The polyethylene fibers are prepared for radiation-induced grafting. The first step in the process is irradiation by an electron beam accelerator (I). The irradiation process generates free radical sites for the subsequent grafting process. The irradiated fibers are placed into stirred tank reactors (L) on bobbins; the rectors are fed the following sequence of chemicals to graft an amidoxime group onto the radical sites on the polyethylene backbone:

1) 5 percent (by weight) surfactant (sodium lauryl sulfate) and 30 percent (by weight) acrylonitrile in water,

2) dimethylformamide (DMF),

3) 3 percent (by weight) hydroxylamine in 1:1 water/methanol solution.

The grafted adsorbent fibers are subsequently woven around floats on a braiding machine (N) to complete the adsorbent manufacturing process.

Details of individual equipment sizing and costing and operating costs for adsorbent production are detailed in the online Appendix (part B). The equipment costs for the adsorbent production area are summarized in Table 2. The table includes references to equipment IDs on the corresponding PFDs in the

Table 2: Equipment table with delivered equipment costs, grafting-braiding area (2010 USD).

ID (s) from PFD	Equipment	Type	Qty	Size	Unit	Total purchased equipment cost (USD)
A	Polymer Extruder	Single Screw	7	250	mm	See Melt Spinning Total
D	Spinneret	Melt Spinning	238	200	holes	See Melt Spinning Total
G	Final Take-Up	Roll/Winder	—	3300	m/min	See Melt Spinning Total
N/A	Melt Spinning–All Equipment	All	—	50,000	tonnes/ year	8.69 MM
I	Electron Beam Accelerator	Direct Current	1	0.9 160 145	MeV mA kW	2.30 MM
K,M,O	Solids Conveying	Belt Conveyor	1	1514	M	2.25 MM
L	Grafting Reactors	Jacketed, Stirred Reactors	77	4	m^3	4.49 MM
N	Braiders	N/A	1275	N/A	N/A	11.9 MM
N/A	Acrylonitrile Storage	Tanks (316 SS)	2	2,007	m^3	1.03 MM
N/A	Surfactant Storage	Tanks (316 SS)	1	312	m^3	150 K
N/A	Hydroxylamine Storage	Tanks (316 SS)	1	2,024	m^3	520 K
N/A	DMF Storage	Tanks (316 SS)	3	2,079	m^3	1.59 MM
N/A	Water-Methanol Storage	Tanks (316 SS)	3	2,027	m^3	1.56 MM
Total Delivered Equipment Cost (1.1* Total Purchased Cost)						38 MM

online Appendix (part A, Figure A.1 and Figure A.2). Braider costs were taken from Tamada. Equipment sizing and reaction data from Tamada unless indicated. Storage tanks were sized for a 30-day inventory.

Operating costs include labor, utilities, and materials costs. A detailed discussion of operating costs is included in the online Appendix (part B); results are summarized here. Labor requirements and costs were estimated for the entire adsorbent production area. The PFDs for the adsorbent production area (Figure A.1 and Figure A.2) enumerate the major process steps used for labor estimation. The labor requirements for adsorbent production are summarized in Table 3.

Unit costs and data sources for chemicals and utilities are given in Table B.7 and Table B.8, respectively, in Appendix B. Total annual consumption and costs for chemical and utilities are summarized in Table 4 and Table 5. The code of accounts for the adsorbent production area can be found in Table C.1.

Table 3: Summary of annual labor requirements and costs—adsorbent production area at a design capacity of 50,000 tonnes HDPE fiber/yr (2010 USD).

	Man-hours	Operators	Burdened cost per employee	Total cost (MMUSD)
Melt Spinning and Irradiation	103,000	53	83 K	4.39
Grafting and Braiding	51,600	27	83 K	2.24
Total for Adsorbent Production				6.63

MOORING AND DEPLOYMENT

The mooring, deployment, and retrieval of the braid adsorbents at the selected coastal site requires marine transportation and mooring equipment such that braid adsorbents can be recovered and re-deployed at rates consistent with the annual uranium production target. This section summarizes mooring and deployment system parameters and costs.

The design of the adsorbent field, recovery and deployment processes and equipment, and site selection were evaluated to populate a code of accounts. Design parameters and base case values from the Japanese analysis are summarized in Table 6.

The mooring chains (stud-link anchor chains) are central to the design. The chains serve as the anchor for the braid adsorbents which are buoyant due to the embedded float in the backbone of each adsorbent unit. The chain

Table 4: Summary of raw material costs and annual chemical requirements for adsorbent production area. Design capacity of 50,000 tonnes fiber per year (2010 USD).

Chemical	Annual consumption	Unit cost (USD per tonne)	Total cost (MMUSD)
High Density Polyethylene	50,000 tonnes	1,470	73.4
100% Hydroxylamine Hydrochloride	56,400 tonnes	3,080	174
100% Acrylonitrile	35,400 tonnes	1,330	47.2
100% Surfactant (Sodium Dodecyl Sulfate)	3,450 tonnes	2,100	7.24
Methanol	52,900 tonnes	284	15
Dimethylformamide	64,800 tonnes	1,250	80.7
Total for Adsorbent Production			397

Table 5: Summary of annual utility requirements and costs for adsorbent production area. Design Capacity of 50,000 tonnes fiber per year (2010 USD).

Utility	Annual consumption	Unit cost (USD)	Total cost
Electricity	620,000,000 kWh	0.069/kWh	42.9 MM
Process Water	1,070,000 tonnes	0.07/tonnes	77.9 K
Deionized Water	444,000 tonnes	1.08/tonnes	48 K
	Total for Adsorbent Production		43.4 MM

also dictates the method and apparatus to recover saturated adsorbent from the field. An anchor windlass (a specialized class of winch designed specifically for stud-link chain recovery) is needed to pull the chain up from the ocean floor to allow removal and replacement of saturated adsorbents. The speed with which the windlass can recover the chain determines how much adsorbent each ship can recover in a given period of time and ultimately the number of ships required. Finally, the ships transport the adsorbent to and from onshore facilities, carry required work crew for recovery operations, and house the anchor windlass for chain recovery. The ships are defined by their carrying capacity in deadweight tonnes (dictates the amount of adsorbent each ship can carry) and brake horsepower.

Based on the chain requirements to moor the 100,000 tonnes of adsorbent, JAEA developed the field design shown in Figure 2. Previous analysis by the authors showed that chain sizing is limited by dynamic forces on the chain during recovery (as opposed to static forces during deployment); the

Table 6: Adsorbent mooring field parameters[3]

Parameter	Value	Units	Notes
Adsorbent Deployment	100,000	tonnes/year	Based on 1200 tonnes per year uranium requirement, 2 gU/kg Ads capacity, 60 day campaigns, and six reuses of adsorbent
Adsorbent Linear Density	1	kg/meter	
Braid Length	60	Meters	
Braids Required	1.67 M	Braids	
Braid Spacing	8	Meters	To prevent entanglement
Length of Individual Chains	2,120	Meters	
Chain End Length	100	Meters	Unencumbered ends of chain for handling
Braids per Chain	240	Braids	Based on spacing and end requirements
Chains Required	6,976	Chains	To moor 100,000 tonnes of adsorbent

Table 7: Mooring vessel requirements and sizing specifications

Item	Value	Unit	Comments
Length of Campaign	60	Days	Boat campaign and adsorbent soaking times are taken to be equal
Required Daily Chain Recovery	116	Chains/day	Based on exchange of all adsorbent over the campaign
Chain Recovery Speed	4	Meter/minute	JAEA Assumption
Boat Operation/Day	9	Hours	Assumption
Time to Recover One Chain	9	Hours	Calculated - 1 boat
Total Boats Required	116	N/A	Calculated
Loaded Adsorbent Weight	107,000	Tonnes	Weight of adsorbent + 2 × weight of known adsorbed metals
Boat Capacity (Dead Weight)	1000	Deadweight tonnes	Calculated from adsorbent transported per boat
Ship Brake Horsepower	861	BHP	Calculated from empirical relationship.[1] See Appendix B.

[1]From Cullinane, Kevin, and Mahim Khanna.

calculations of working load on the chains confirmed the JAEA specification of 44 mm anchor chain.[9]

Work boat requirements are determined by the adsorbent field size and the speed at which each ship can recover the anchor chain. Sizing results for mooring equipment are shown in Table 7 and Table 8 with supporting calculations in Appendix B.

An economic analysis of shipping by Cullinane and Khanna (see Appendix B) was used to derive fuel and personnel requirements;[10] the results are summarized in Table 9 and Table 10.

Table 8: Equipment table with delivered equipment costs for mooring area (2010 USD).

Equipment	Type	QTY	Size	Unit	Total Purchased Equipment Cost (USD)
Mooring Chains	Stud Link Anchor Chain	6976	44	mm	1.43 B
Windlass	N/A	116	36	kW	Included in Ship Costs
Ships	Cargo	116	1000 861	DWT BHP	510 M
Total Delivered Equipment Cost (1.1*Total Purchased Cost)					2.13 B

Table 9: Summary of utility costs and requirements for mooring area. Design capacity of 100,000 tonnes adsorbent field (2010 USD).

Utility	Annual consumption	Unit cost (USD)	Total cost (MM USD)
No. 2 Fuel Oil	12 M gal	2.12/gal	25.4
Total for Mooring and Recovery			25.4

A preliminary analysis was performed to consider the cost and performance impact of a mooring site location along the coastline of the continental United States. In addition to costs associated with obtaining offshore space to operate the adsorbent field, the conditions of specific sites may impact performance of the adsorbent or feasibility of the mooring system due to temperature, depth, or other environmental factors. Therefore, as reported in prior analyses, five coastal regions in the United States were evaluated for potential lease cost, depth of water in coastal areas, and temperature of water as a function of depth.[11] The results of the site selection analysis found depth-averaged temperature varying from 17 to 25°C across the sites and lease costs ranging from \$1800 to \$2200 per km^2 (2010 USD). The temperature is an important factor in adsorbent capacity as discussed in the online Appendix (part D).

Finally, several previous studies used 3 to 5 percent of the initial capital cost as an estimate for all other operating costs (including maintenance, taxes and insurance, administration, etc.).[12] A nominal value of 4 percent is used here while the range is used in analysis of uncertainty in costs. The code of accounts for the mooring and deployment area summarizes all component costs and can be found in Table C.2.

ELUTION, PURIFICATION, AND DISPOSAL

The recovery of the uranium from the adsorbents entails two processes: elution of metals from the adsorbent and purification of uranium to produce purified ammonium diuranate (ADU). Treatment and disposal of the used polymer is also discussed.

Table 10: Summary of labor costs and requirements for mooring area. Design capacity of 100,000 tonnes adsorbent field (2010 USD).

	Total fleet requirement	Burdened annual cost (USD)	Total cost (MM USD)
Ship Captains	116	108,000	12.6
Sailors/Workers	1,856	58,500	109
Total for Mooring and Recovery			121

The elution and purification processes are divided into three separate PFDs with associated equipment tables in Appendix A (Figure A.3 with Table A.3, Figure A.4 with Table A.4, and Figure A.5 with Table A.5). Several support processes are not depicted in the main process flow (i.e., raffinate treatment, sump recovery, and acid recovery). However, these additional process areas are included in the cost estimation scope. The PFD in Figure A.3 for the elution process was developed from the process description given by JAEA; equipment sizing was taken from the Japanese cost estimation, but equipment costs were developed independently.

The loaded adsorbent is transported to the first elution tank (A); in this stirred reactor vessel, the alkali and alkali earth metals present in the adsorbent are eluted with 0.01 M hydrochloric acid. After the initial wash, the adsorbent is transferred to a second elution tank; the uranium in the adsorbent is eluted with 0.1 M nitric acid. The fractional elution process was developed by Japanese researchers to isolate uranium from the other constituents adsorbed from seawater.[13] The stripped adsorbent proceeds to an alkali wash to remove residual acid and regenerate the adsorbent prior to recycle to the sea (F).

Following the elution, the uranium, now in solution as uranyl nitrate, is subjected to a purification process that follows the practice at conventional surface mines. Specifically, the uranyl nitrate is pumped to a storage/surge tank (G) followed by a precipitation tank (H); ammonia is added to the tank to precipitate uranium from solution as crude ADU which requires further purification. First, the ADU is sent to a thickener (I) and centrifuge (J) to remove any excess liquids or contaminants prior to further processing. Finally, the ADU is dried (L) and prepared for purification.

The crude ADU is re-dissolved in concentrated nitric acid in a stirred tank (N) to once again form uranyl nitrate that serves as the initial feed for the purification circuit. The purification process is analogous to uranium refining processes used for conventionally mined ores; specifically, the process used in this design is a tri-butyl phosphate (TBP)—hydrocarbon diluent and nitric acid solvent extraction process based on a design for conventional uranium refining.[14]

The details of sizing and cost calculations for the elution purification process are developed in the online Appendix B; the results are summarized in Table 11.

Labor requirements and costs were estimated for the back end process. The PFDs (Figure A.3, Figure A.4, Figure A.5) provide the number of major process steps used in labor calculations and the calculation methodology is detailed in Appendix B. The labor requirements for the elution-purification area are summarized in Table 12.

Raw materials and utilities consumption were taken from the JAEA assessment for the elution process; the Fernald refinery design report included raw materials and utilities consumption values that were used as the basis for the purification operating costs.[15]

Table 11: Equipment table with delivered equipment costs for elution-purification area (2010 USD).

ID (s) from PFD	Equipment	Type	QTY	Size	Unit	Total purchased equipment cost (USD)
A,C,E,K	Solids Conveying	Belt Conveyor	1	3,000	m	4.45 MM
B, D	Elution Tanks	Field Erected Tanks w/3 kW Agitator	2	642	m^3	454 K
N/A	Nitric Acid Storage Tank	Field Erected Tanks	3	1,752	m^3	1.38 MM
N/A	Hydrochloric Acid Storage Tank	Field Erected Tanks	12	2,467	m^3	7.38 MM
See Figure A.5	Purification Area	Multiple	—	1,200	tonnes U per year	4.52 MM
See Figure A.4	Precipitation Area	Multiple	—	1,200	tonnes U per year	4.27 0MM
Total Delivered Equipment Cost (1.1*Total Purchased Cost)						24.7 MM

For the precipitation area, detailed utility costs were not available; as a preliminary estimate, utility costs for the precipitation area were estimated as 4 percent of the delivered equipment cost. This matches the ratio of the utilities to equipment costs for the purification area. Raw materials consumption (ammonia) was taken from the JAEA assessment. Unit cost estimates for utilities and chemicals were used to estimate total raw materials (Table 13) and utilities costs (Table 14) for the back end processes.

The remaining operating costs (e.g., management labor, maintenance, supplies, etc.) were estimated by the methods summarized in Appendix B. The costs can be found as part of the COA for the elution-purification area in Appendix C (Table C.3).

The JAEA analysis assumed that disposal of used adsorbent could be achieved at negligible cost. JAEA envisioned incineration of the polymer as a volume reduction measure, leaving a residue amenable to inexpensive landfill disposal. A further option, that could potentially lead to a degree of material cost recovery, would be to recycle the braid material as a source of high-density polyethylene (HDPE). Considerable industrial experience exists with the

Table 12: Summary of labor requirements and costs for elution-purification area. Design capacity of 1200 tonnes uranium per year) (2010 USD).

	Man-hours required	Operators required	Annual operator salary (USD)	Total cost (MMUSD)
Elution	31,600	17	83,000	1.4
Purification	101,000	52	83,000	4.3
Precipitation	62,400	32	83,000	2.7
Total for Elution and Purification				8.37

Table 13: Summary of annual chemical requirements and raw material costs for elution-purification area. Design capacity of 1200 tonnes uranium per year (2010 USD).

Annual chemical requirements ()			
Chemical	Annual consumption (tonnes)	Unit cost per tonne (USD)	Total cost (USD)
67% Nitric Acid	5,180	284	1.47 MM
36% Hydrochloric Acid	383	148	56.6 K
Sulfuric Acid, 66°Be	73	63	4.6 K
Sodium Carbonate	7	149	1.04 K
TBP	4	6420	25.1 K
Kerosene	11	553	6 K
Filter Aid	0.07	325	22
Magnesium Oxide	61	598	36,500
Ammonia	0.45	341	153
Calcium Oxide (Lime)	27	107	2,900
Total for Elution-Purification			1.61 MM

recycle and reconstitution of post-consumer HDPE; even assuming the HDPE is not suitable for use in consumer products, it might find use in building or paving materials.[16] In the best case, the recovered HDPE could be directly recycled to the adsorbent fabrication process, obviating the need to continue to purchase virgin HDPE.

Here it is conservatively assumed that the adsorbent must be disposed and factors unique to the uranium recovery process may impose constraints on the disposal method. Specifically, the used adsorbent may retain uranium along with numerous other elements adsorbed during the seawater immersion campaigns. A conservative approach would handle the used adsorbent as so-called 11.e(2) waste, a U.S. Nuclear Regulatory Commission classification. Appendix B provides details on disposal costs of 11.e(2) wastes derived from previous

Table 14: Summary of annual utility costs and requirements for elution-purification area. Design Capacity of 1200 tonnes uranium per year (2010 USD).

Utility	Annual consumption	Unit cost (USD)	Total cost (USD)
Electricity	2,840,000 kWh	0.069/kWh	196,000
Process Water	304,000 tonnes	0.07/tonnes	22,000
Deionized Water	184,000 tonnes	1.08/tonnes	199,000
Steam	1,630 tonnes	32/tonnes	52,200
Cooling Water	741,000 m^3	16.01/1000 m^3	11,900
Purification – All (4% of Delivered Equipment Cost)	N/A	N/A	188,000
Total for Elution-Purification			669,000

work related to disposal of spent ion-exchange resins. The analysis resulted in a disposal cost of $0.360/kg adsorbent which is applied as a fixed, fee for service cost in this analysis.

The code of accounts for the elution-purification and disposal area is summarized in Table C.3.

URANIUM PRODUCTION COST AND UNCERTAINTY: METHODOLOGY

This section describes the life cycle discounted cash flow (LCDCF) methodology employed to calculate the uranium production cost from the cost inputs described in the previous section. The discussion includes implementation of COA-structured input cost data in the LCDCF method. In addition, uncertainty quantification has not previously been undertaken in seawater uranium cost estimation. Therefore, this section also provides an outline of the uncertainty propagation methods employed to derive production cost confidence intervals.

Life Cycle Discounted Cash Flow Methodology

The LCDCF approach is used to track cash flows over the life cycle of an arbitrarily chosen mass of one tonne of adsorbent. The costs and benefits (i.e., uranium production) are tracked over the lifetime of the adsorbent. Thus the costs described in the previous section must be normalized to a single tonne of adsorbent. The time(s) at which costs are incurred are recorded as events over the lifetime of the adsorbent. Similarly, the uranium recovery from the single tonne of adsorbent becomes a series of events over the lifetime of the adsorbent. The widely used cash flow analysis methodology is described in the Gen-IV EMWG cost estimation guidelines.[17]

In a discounted cash flow analysis, a reference time must be selected. In this study, "time zero" is defined as the time at which the unit mass of adsorbent is first immersed. Adsorbent production costs are incurred prior to "time zero." The timing of this manufacture relative to the first immersion in seawater is important in the discounted cash flow analysis since all of the operating, maintenance, and material costs for adsorbent manufacture are incurred prior to revenue generation. In this analysis, the adsorbent production cost was assumed to be incurred 0.5 years prior to initial deployment. Longer lead times would lead to larger present values for adsorbent production costs.

The costs and benefits of the adsorbent production system are distributed over time and depend on the duration of the per-recycle immersion and recovery periods. Table 15 provides a timeline for the lifetime of a unit mass of adsorbent highlighting events associated with costs and benefits.

Annual operating costs and uranium production are discounted to reflect the time value of money; the uranium production is a proxy for the revenue

Table 15: Lifetime of a unit mass of adsorbent.

Time (years)	−0.5 ↓	0 ↓	0.16 ↓	0.27 ↓	***	1.33 ↓	1.43 ↓	1.59 ↓
Event (s)	Adsorbent Production	Initial Deployment	Recovered to ship	Return to Shore Uranium Recovery 2nd Deployment		Return to Shore Uranium Recovery 6th Deployment	Recovered to Ship	Return to Shore U Recovery Disposal

stream that would be associated with sale of the product. Cash flows are discounted using a present value factor as follows:

$$Discounted\ Cash\ Flow = Cash\ Flow * PVF \tag{2}$$

where

PVF = present value factor = $(1 + i)^{-n}$
i = discount rate; 7% base value (1/year) [18]
n = time of cash flow occurrence relative to reference time (year)

Capital costs are amortized using a separate interest rate of capital (e.g., 10 percent interest rate of capital over 15 years for equipment in the base case). The interest rate of capital and discount rate were differentiated to reflect an additional risk premium associated with the large initial cash outlay and uncertain return on investment. Amortized annual cash flows reflect the cost of capital financed with debt or equity as well as interest during construction (see Appendix B for a discussion of interest during construction).

The code of accounts provides total project costs by specific categories. To associate the annual costs from the COA with a single tonne of adsorbent in the LCDCF approach, three steps are taken:

1) Amortized annual capital costs are prorated to the portion that is defrayed by the unit mass of adsorbent. Annual operating costs are prorated according to the capacity or throughput taken up by the unit mass. All amortized capital and discounted operating costs incurred over the lifetime of the absorbent are summed to arrive at a life cycle cost in dollars.

2) The uranium production over the lifetime of the unit mass is discounted and summed. Uranium production occurs at the end of each purification step; in the reference case, a unit mass of adsorbent thus produces uranium at six discrete points in time. It is appropriate to discount the uranium production as this reflects the discounting of the revenue stream that would be associated with uranium sale. This step yields discounted uranium production over the adsorbent lifetime in kilograms of uranium.

3) The life cycle cost from 1) is divided by the discounted uranium production from 2) to yield a unit cost of uranium production in dollars per kilogram of uranium.

PROPAGATION OF UNCERTAINTIES

The methodology developed thus far employs a deterministic approach to cost estimation; however, many of the heuristics, scaling assumptions, and process inputs used to develop cost estimates are uncertain. Much of the data is accompanied by a range of feasible values or takes the form of a mean or expected

value derived from underlying datasets. These uncertainties in input variables must be propagated through the analysis to depict the uncertainty associated with the uranium production cost. Estimates of uncertainty were developed for all cost inputs and two performance inputs (adsorption capacity and degradation rate).

Table B.10 in Appendix B summarizes all relevant input parameters and the mean and standard deviation of each distribution. All parameters were assumed normally distributed. In addition, the data source for each parameter is categorized in the final column of the table as a data set, range, or point estimate; this dictates the method used for estimation of the uncertainty. For a data set, the standard deviation for the data was used directly as a measure of variability. For parameters reported as a range, the midpoint of the range was treated as the mean and the endpoints of the range, represented two standard error deviations from the mean (95 percent confidence interval). In the case of a point estimate, two standard error bounds were represented as +/−30 percent of the point estimate; this is consistent with uncertainty expected in order of magnitude engineering estimates (see Table B.4 in Appendix B). A Monte Carlo stochastic estimation approach was used for propagation of uncertainty.

Performance uncertainties (final two rows of Table B.10) reflect variation in actual field performance. In the case of adsorbent capacity, statistical analysis of JAEA field test data was used to approximate uncertainty associated with the performance of the technology.[19] The analysis led to a normally-distributed estimate of adsorbent capacity that exhibited, in 25°C water and 60 day immersion, a mean of 2.0 kg U/t ads and standard deviation 0.50 kg U/t ads (Appendix D). For adsorbent degradation, Japanese data provided a point estimate from a single observed data point of approximately 20 percent loss in adsorbent capacity after 5 recycles (5 percent loss per recycle).[20] The uncertainty around the degradation could not be quantified from a single data point; instead it was taken as +/−2.5 percent per recycle to ensure that the 95 percent confidence intervals for degradation included the possibility of no degradation (the assumption in previous JAEA analysis).

RESULTS AND DISCUSSION

Base Case

The base case for the current analysis (Table 1) represents the performance of the Japanese system observed in field tests.[21] Financial and performance parameters match those of the Japanese data source, unless specifically noted in Table 1.

Specifics for interest during construction are covered in Appendix B. Table 16 provides a summary of total capital investment and annual operating

Table 16: Total Capital Investment Cost and Operating Cost Summary for Base Case (2010 USD).

	Capital investment cost[1]		Annual operating costs	
	Total (MM USD)	Contribution to unitcCost (USD/kg U)	Total (MM USD/year)	Contribution to unit cost (USD/kg U)
Adsorbent Production	187	23.60	512	531.00
Mooring and Recovery	2350	309.00	257	247.00
Elution and Purification	122	15.40	25.7	24.20
Interest During Construction	474	50.30		
Adsorbent Disposal Charge[2]			36	32.40
TOTAL[3]	3133	399.00	831	834.00

[1]Capital investment costs for each process area are estimated using the methods outlined in Appendix B using the equipment costs presented in this work as the basis for estimation.

[2]Adsorbent Disposal Charge is fee for disposal service occurring as adsorbent reaches end of lifetime.

[3]To derive the unit production costs from the total capital and annual operating costs in this table, the life-cycle cash flow method described the discussion of cash flow methodology should be applied to the aggregate costs in Table 16. This methodology will account for time value of money (for costs incurred and uranium produced) and the degradation of the adsorbent with time.

costs for the base case. Appendix B provides the calculations required to derive the aggregate costs in Table 16 from the component costs presented in the input cost assessment section; the COA tables in Appendix C provide detailed component costs for each category. As described in the appendices, the unit uranium production cost components (in $/kg U) presented in the table incorporate amortization and time value of money effects as well as adsorbent performance degradation.

The uranium production cost results for the base case are shown in Figure 3. It includes uncertainties in costs, actual performance, and durability and was generated by Monte Carlo analysis where costs and performance variables were sampled from independent normal distributions, as described in the cost and uncertainty methodology section. The height of the histogram bars (read against the left-hand scale) measure the relative likelihood that a Monte Carlo 'history' will fall within each uranium production cost bin. The solid line, read against the right-hand axis, plots the fraction of histories with uranium production costs falling below a given level.

If all cost and performance parameters take on their expected values, the nominal uranium production cost is $1230/kg U; however the uncertainty

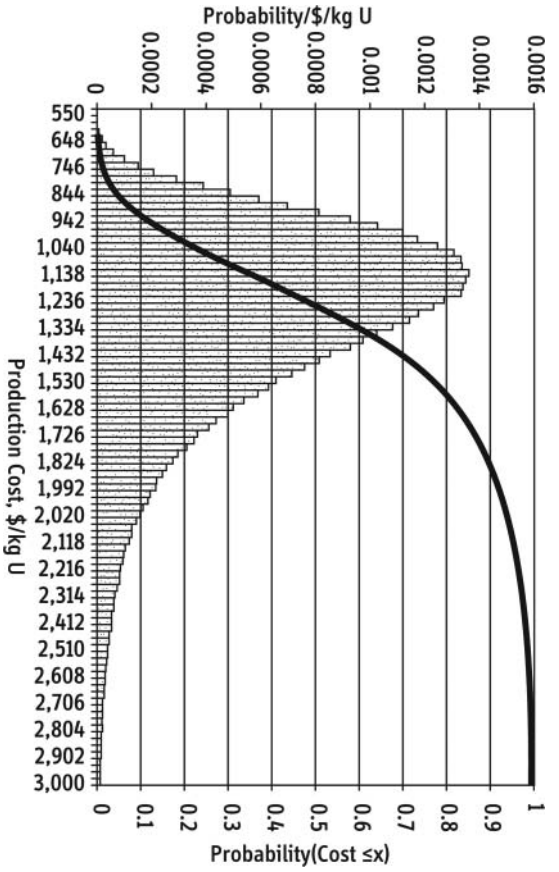

Figure 3: Histogram of base case cost estimate, cost and performance uncertainties included.

associated with this result is considerable. Define a 95 percent confidence interval as the cost range inside of which 95 percent of histories fall. This confidence interval for the base case is [$806/kg U, $2430/kg U] and is dominated by uncertainties in capacity and degradation rate.

If the performance of the current adsorbent technology were better-quantified, so that it could be said with certainty that the capacity is 2 kg U/t ads, then the 95 percent confidence interval would narrow to [$997/kg U, $1500/kg U]. If the degradation rate with recycle were known to be 5 percent with no uncertainty, only the cost uncertainties would remain and the interval would narrow further to [$1040/kg U, $1440/kg U].

Figure 4 depicts the discounted cash flow diagram for the base case. Revenue associated with the sale of uranium is shown as positive values; costs are disaggregated by category and time they are incurred relative to the time the adsorbent is first immersed. The declining revenue stream with each recycle

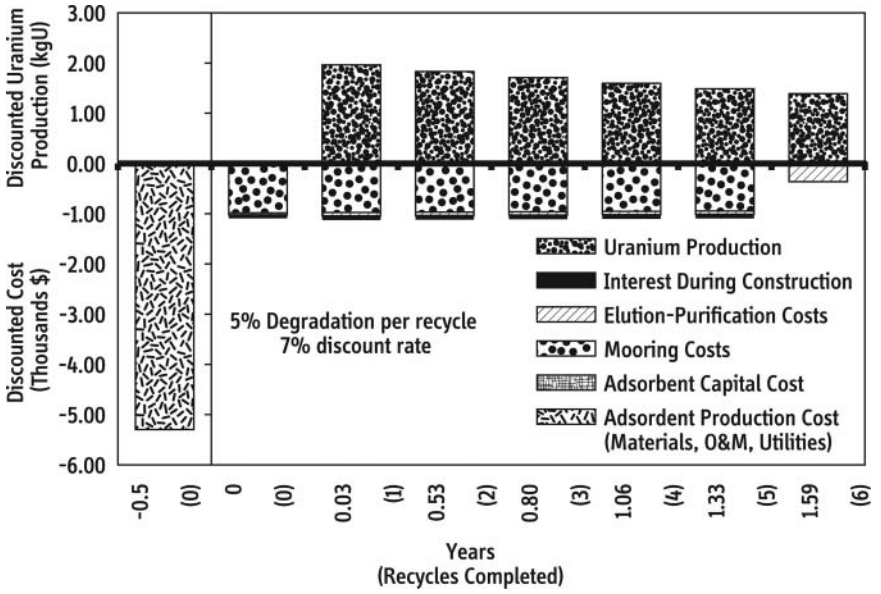

Figure 4: Life cycle discounted cash flow diagram for base case analysis at 6 recycles.

reflects the impact of both capacity degradation and the time value of money reflected in the 7 percent discount rate. The chart also highlights a key cost driver, adsorbent production, as a large cost incurred prior to operation.

Figure 5 depicts the components of the uranium production cost for the base case conditions. Adsorbent costs, largely consisting of grafting chemicals consumption, represent a significant portion of the project costs and thus an important development area for amidoxime adsorbent fibers.[22] The mooring costs provide a second important area for potential cost reduction, making up 45 percent of the unit uranium production cost. The subsequent sensitivity analyses will consider component costs in further detail.

SENSITIVITY ANALYSES

Two critical uranium production cost drivers, capacity and number of recycles, are varied in Table 17. All other inputs remain unchanged from those defined in Table 1. The base case defined earlier appears in the first row of the table. In Table 17, increases in capacity are imposed without varying the 60 day immersion time. Hence they reflect hypothesized advances in the underlying adsorbent technology. Such advances would be expected to perturb the process flow sheets and associated costs. Therefore, the results should be interpreted as reflective of the production cost only if the perturbations required to achieve the higher capacity have a minimal impact on the cost inputs. Variation of the

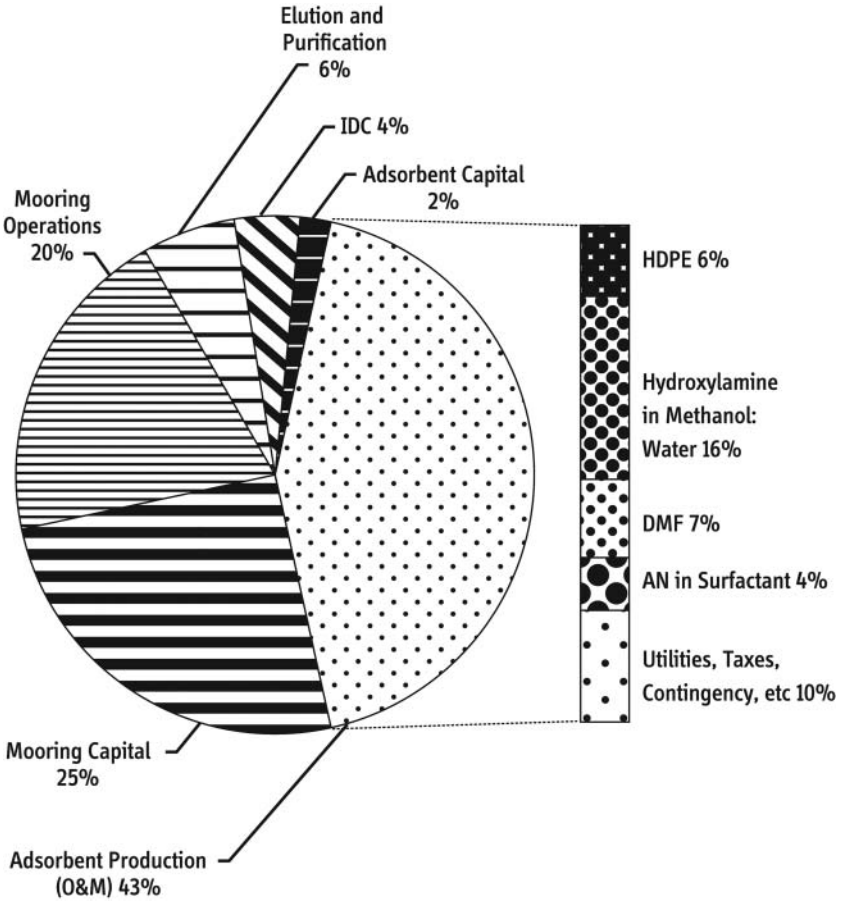

Figure 5: Unit uranium production cost by major cost areas with a focus on adsorbent production.

immersion time, which changes the capacity of the current adsorbent from the nominal 2 kg U/t ads seen at 60 days immersion, is considered separately.

For each case, the expected value of the production cost is reported alongside a set of 95 percent confidence intervals. The first of these confidence intervals reflects the overall uncertainty if all its contributors (capacity, degradation, input costs) are varied. To facilitate understanding of the contribution of each uncertainty component, the final three columns depict the 95 percent confidence interval if only one uncertainty contributor is allowed to vary.

The table includes several alternate cases. JAEA proposed 4 kg U/t ads as a feasible capacity and viewed the 6 kg uranium capacity as an optimistic case; 18 recycles was also considered an optimistic estimate.[23] Note that when capacity degradation is taken into account at the current experimentally

Table 17: Summary of uranium production cost estimation results for base case and alternatives including uncertainty quantification (2010 USD).

Capacity (kgU/t ads)	Recycles	Cost, expected value (USD/kgU)	95% confidence intervals (USD/kgU)			
			Overall	Capacity[1]	Degradation[2]	Cost[3]
2	6	1230	2430	2370	1290	1430
			806	853	1200	1030
2	18	1180	2440	2220	1470	1400
			681	820	1000	956
4	6	659	1240	1220	691	765
			430	451	644	553
4	18	642	1280	1180	803	761
			371	441	543	523
6	6	450	848	819	477	522
			303	327	439	378
6	18	440	886	818	553	523
			262	329	373	358
20	1	408	759	741	N/A	477
			275	290	N/A	339

[1]Capacity refers to uncertainty in adsorbent performance; see the discussion on the propagation of uncertainties and Appendix B.

[2]Degradation rates have only been quantified as point estimates. A normal distribution about the reference value of 5 percent degradation per pass (standard deviation: 2.5 percent degradation per pass) was assumed.

[3]Cost uncertainty includes variability in prices of equipment, chemicals, and estimation techniques as described in the results.

demonstrated level, the cost benefit associated with increasing the number of recycles from 6 to 18 is marginal. Unlimited recycle is optimal only in the limit of no capacity degradation with re-use. In addition, the final scenario in the table represents an alternate design target: a high capacity, single-use adsorbent material.

As expected, the degradation rate uncertainty component increases in significance as the number of recycles is increased. Many of the cost inputs were assigned a standard deviation of 30 percent (in the absence of data for statistical evaluation of uncertainty). Others were given values reflecting historical volatilities. Yet the input cost uncertainties, when propagated, give rise to significantly less than 30 percent uncertainty in the uranium production cost because all uncertainties were treated as uncorrelated and sampled independently. In the opposite (and unrealistic) extreme case where all cost uncertainties were treated as perfectly correlated, the input cost uncertainty component would rise significantly.

Other system design parameters are varied in Table 18. All entries in the table reflect perturbations of a single parameter from the base case values given in Table 1 or elsewhere. For each perturbation, the percentages show

Table 18: Summary of parameter sensitivity analyses.

Variable	Low cost point	Percent change	Base case values[1]	Percent change	High cost point
Discount Rate (%)	0	*−5.9*	7	*6.8*	15
Interest Rate of Capital (%)	3	*−13*	10	*10*	15
Recycles	18	*−4.4*	6	*33*	3
Seawater Temperature (°C)	30	*−10*	25	*42*	15
Adsorbent Performance Loss (%/Recycle)	0	*−12*	5	*13*	10
Adsorption Capacity (g-U/kg-ads)	6	*−63*	2	*93*	1
Annual Consumption of Hydroxylamine (tonnes)	28 K	*−8.1*	56 K	*15*	110 K
Annual Consumption of Acrylonitrile (tonnes)	17 K	*−2.3*	35 K	*4.3*	70 K
Consumption of DMF (tonnes)	32 K	*−3.8*	65 K	*7.5*	130 K
Size of Mooring Chain (mm)	38	*−3.4*	44	*5.6*	50
Annual Uranium Production Capacity (tonnes)	4800	*−3.5*	1200	*22*	300

[1]Base Case conditions include 2 g U/kg ads, 6 recycles, 5 percent degradation. All percentages are differences from the expected uranium production costs at the base case conditions, $1230/kg uranium.

the change in the uranium production cost relative to base case value of $1230/kg U.

If both financial parameters are returned to the values used in the JAEA study (i.e., zero percent discount rate and three percent interest rate of capital), the uranium production cost would decline by 18 percent to $1013/kg U, close to the JAEA cost estimate of $995/kg U.

The seawater temperature perturbation uses the kinetics model presented in Appendix D. Sensitivity results indicate that operations at temperatures around 15°C may never be attractive. Note that the experimental data that informed the kinetics model was limited and further study of adsorption kinetics is ongoing at Oak Ridge National Laboratories.

The largest single cost component for the reference case is chemicals employed in the grafting process. If their annual consumption could be reduced to half of their base case levels, the uranium production cost would drop by 14 percent (over $170/kg U).

Economies of scale exhibit a minimal effect on production costs at large annual capacities: increasing the annual U production capacity of the adsorbent field from 1200 tU/yr to 4800 tU/yr decreased costs by less than 4 percent.

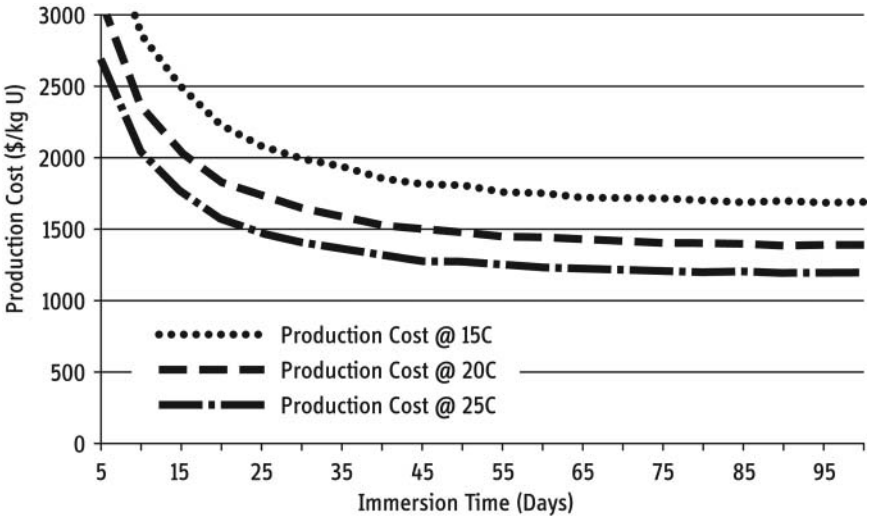

Figure 6: Production cost as a function of immersion time and seawater temperature.

Many of the largest cost components, for instance mooring chains, recovery boats and chemicals, do not benefit from economies of scale. However, the current scope of analysis did not include scale effects in chemical production processes for input materials.

Figure 6 makes use of the statistical model of the time and temperature dependence of capacity introduced in the online Appendix (part D) to estimate the correlation between immersion time, water temperature and uranium production cost. As before, all conditions other than these (and the adsorption level in kg U/t ads, which is now derived from them) were taken to assume their base case values. Since the adsorption rate decreases as immersion time increases, the benefit of longer-duration immersions (increase in the uranium yielded per deployment-recovery operation) comes to be offset by the attendant increase in the overall field size needed to attain the desired annual uranium production capacity. In addition, the reduced time value of a delayed and protracted the revenue stream associated with each unit of adsorbent also acts to increase uranium production costs. It is evident that given current understanding of the kinetics of the adsorbent, 60 days remains a reasonable duration target for the immersion campaigns.

The optimal number of recycles in the presence of capacity degradation is explored further in Figure 7. The figure also illustrates the strong dependence of the uranium production cost on the capacity of the virgin adsorbent. Given five percent degradation, the optimal number of recycles is seen to be 11 at all capacity levels—and this minimized uranium cost ranges from $1120/kg U at 2 kgU/t ads down to $340/kg U at 8 kg U/t ads.

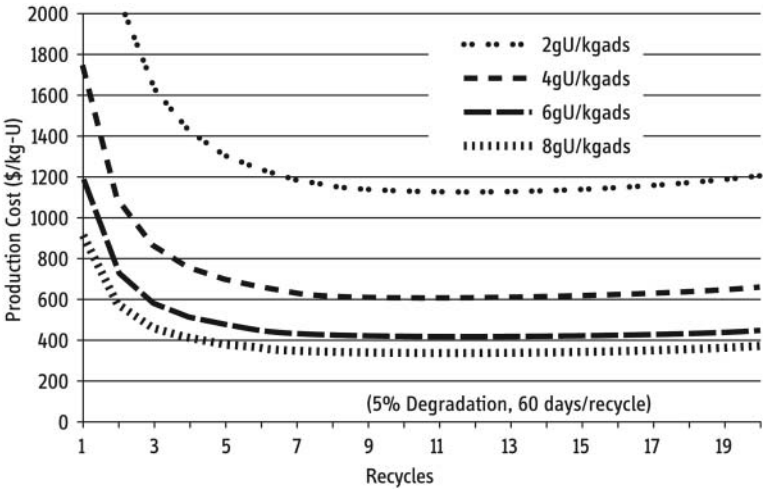

Figure 7: Production cost with varying recycle number and adsorption capacity, base case conditions otherwise.

Finally, Figure 8a–d explores the contributors to cost as number of recycles and degradation rate are varied. Figure 8a compares the uranium production cost for the 2 kg U/t ads virgin capacity level. Figure 8c–d breaks each of these cost curves into their components. In all cases, adsorbent production costs are

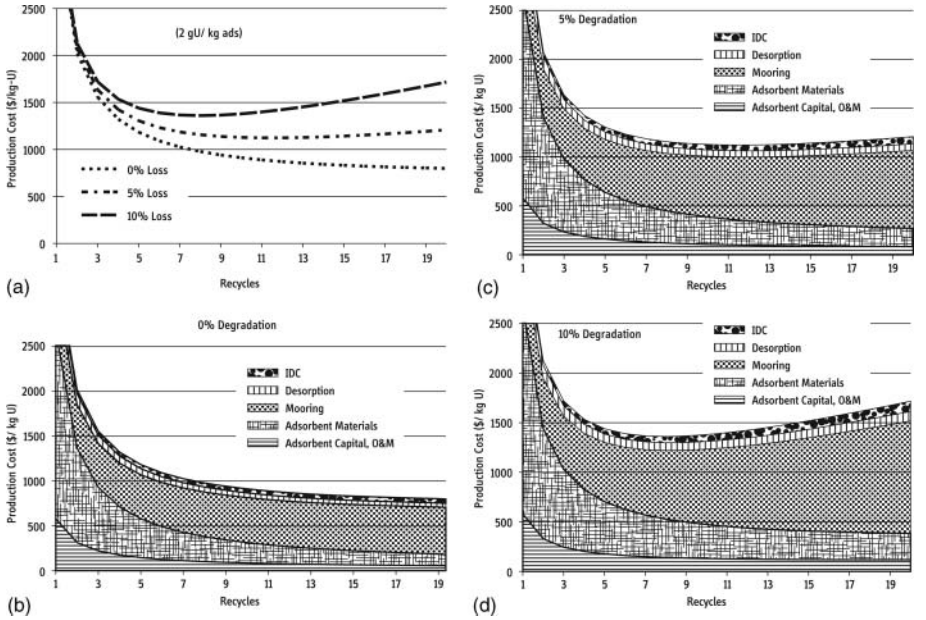

Figure 8: Optimal recycles of adsorbent given varying degradation rates. Figure 8a compares the uranium production cost for the 2 kg u/t ads virgin capacity level; Figures 8c–d breaks each of these cost curves into their components.

seen to dominate if the number of recycles achieved is low, mooring operational costs if many recycles are pursued. Although these operational costs do not themselves change from one recycle to the next, if adsorbent capacity is degrading their contribution to the uranium production cost grows because these fixed per-recycle costs are set against the decreasing benefit of quantity of uranium recovered upon each pass.

The sensitivity analyses confirm the importance of quantifying adsorbent performance and durability; these parameters ultimately drive key cost centers such as chemicals consumption and directly impact the optimization of the other process areas (i.e., mooring and elution).

CONCLUSIONS

The independent component level cost assessment of the amidoxime braid adsorbent in this article is intended to guide future research and investment decisions regarding seawater uranium extraction technology. As such, several key conclusions can be developed.

Using the same reference conditions as JAEA for capacity and recycle (2 kgU/t adsorbent, 6 recycles) as a base case, this study projects the uranium production cost to be $1230/kg U. Therefore, although performance assumptions differ somewhat from those of the JAEA base case and cost inputs were developed independently, this result broadly confirms the order of magnitude of the Japanese estimate of $995/kg U.[24]

Research and development is needed to reduce the uncertainty in the uranium production costs. As noted, when uncertainty in cost and performance are included, the 95 percent confidence interval on the base case (2 kg U/t adsorbent capacity, 6 recycles) is [$806/kg U, $2430/kg U]; when performance uncertainty is removed and only cost uncertainty considered, the 95 percent confidence interval narrows to [$1030/kg U, $1430/kg U]. While cost uncertainties include many factors beyond the control of the investor (e.g., volatility in chemical prices, labor wages, etc.), performance uncertainty can be quantified and reduced. In the current work, limited field data was available regarding the performance (capacity and degradation) of the adsorbent, so the dominance of performance uncertainty as a component of overall uncertainty is directly attributable the lack of data. Therefore, an early step in the technology development should be to extend the performance knowledge base with additional field testing. Reduction of uncertainty has economic value through to the mitigation of risk in future investment and funding decisions.

The analysis also highlighted key cost drivers in the braid adsorbent system. Adsorbent capacity and degradation with re-use are the primary performance measures that influence production costs; adsorbent material and mooring operation and capital costs are the dominant cost components.

The performance parameters, which are the central focus of research and development, should not be optimized in isolation; rather, optimization must occur while considering all relevant system design parameters and costs.

In this work, two broad design paths were evaluated when considering full system costs. One approach is the multi-use or multi-recycle adsorbent scenario. This scenario pays off initial investment in adsorbent production by repeated deployment of the adsorbent. However, the re-use of the adsorbent is constrained by recurring mooring costs and possibly degrading uranium return over time. As shown, these constraints lead to an optimal number of recycles to minimize the uranium production costs. In the absence of degradation, increased recycles lower production costs asymptotically to a minimum production cost. This minimum cost is defined by the mooring component.

The article presented performance goals for both optimization routes to reach similarly aggressive cost reductions. An alternate design path might deploy a high-capacity, single use material. In this case, the initial production costs must be recovered by a high adsorbent capacity (i.e., high uranium return). Assuming unchanged adsorbent production and mooring costs, an adsorbent with a capacity of 20 kg U/ t for single-use has an expected production cost of $408/kg U compared to $440/kg U for adsorbent with a capacity of 6 kg U/ t with 18 recycles and 5 percent degradation per recycle.

To leverage either of the adsorbent development scenarios, new adsorbent materials and production processes may be required. The cost of any new adsorbent materials should be compared to the baseline unit adsorbent production cost of $5.36 /kg adsorbent for the amidoxime braid adsorbent evaluated in this work. Adsorbent production costs are a major cost driver in the final uranium production cost and new materials with prohibitive adsorbent production costs are unlikely to be competitive with the amidoxime polymer-based technology.

Mooring costs also provide opportunities for optimization. Alternatives such as elution at sea (e.g., on board a ship) eliminate the need for moving adsorbent to and from land during operation, reduce recovery vessel size by minimizing onboard storage, and prevent delay in uranium recovery as ships return to shore after campaigns. In addition, mooring site selection may impact adsorbent performance (due to ocean temperatures at specific sites) as well as recovery costs (distance to shore, depth of deployment, etc.).

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Measurements taken for braid-type adsorbents under controlled seawater flow rate conditions have indicated that diffusion is the limiting mechanism. In these experiments, no correlation was seen between bulk flow rate and uranium adsorption at flow velocities extending down to 0.3 cm/sec. The dimensionless mass transfer Biot number, Bi, measures the relative strength of the diffusive and film mass transfer mechanisms. For cylindrical fibers, mass transfer is considered limiting if Bi is less than one and diffusion is Bi is greater than 200. The measurements were used to derive an empirical estimate of Bi on the order of 105–106. C. Tsouris, J. Kim, Y. Oyola, R. Mayes, C. Janke, and S. Dai, "Laboratory and Field Testing of Uranium Uptake from Seawater: Progress Report on First Year's Experiments," FCRD-RES-2012-00175, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, 2012. Therefore, even though drag effects associated with large adsorbent field might reduce the bulk velocity of the seawater inside the field, the performance of the field will evidently be unaffected.

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22. The unit production cost of the adsorbent (includes material, O&M, and capital costs) is calculated at $5.36/ kg adsorbent. Exotic adsorbent materials with significantly higher fabrication costs would only be competitive if their capacity exceeded that of the amidoxime adsorbent by a similarly dramatic margin.

23. Tamada, Masao, Noriaki Seko, Noburu Kasai, and Takao Shimizu.

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